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OPTICALLY ENCODED
PARTICLES WITH GREY SCALE SPECTRA

TECHNICAL FIELD

5 A field of the invention is encoding. Additional exemplary fields of the invention include the life sciences, security, product marking, food processing, agriculture, and chemical detection.

BACKGROUND ART

10 A well-appreciated need for labeling exists in society. Labeling is a fundamental basis for tracking and identifying. Encoding can be used as a form of labeling understood by persons or equipment, as in the case of bar coding. At the microscale, however, labeling/encoding itself becomes difficult.

15 Strategies to encode microscale materials have accordingly received increased attention for such uses as high-throughput screening in the fields of drug discovery, genetics screening, biomedical research, and biological and chemical sensing. Concurrent research strategies for measuring an increased number of analytes while minimizing the necessary sample volume have focused on either on-chip spatially differentiated arrays or encoded beads. Large arrays have been developed for biological and/or 20 chemical sensing purposes by making use of positional encoding to register specific analyte responses. The main advantage of using an array over a conventional single analyte sensor is the ability to process and analyze a large number of analytes simultaneously. Positional arrays, however, can suffer from slow diffusion rates and limits on the concentration ranges of analytes 25 being sensed. An alternative approach is to use individually encoded beads.

Early attempts to encode particles used fluorescent or infrared-active molecules as binary markers. More recently, cadmium selenide quantum

dots have been demonstrated as viable candidates for particle encoding based on their unique fluorescent properties. Quantum dots have the advantage over organic molecules of increased stability towards photobleaching, sharper fluorescence peaks, improved solubility characteristics, and large excitation frequency ranges. With six colors (limited to the peak width of the fluorescence in the visible range) and ten intensity levels, 10^6 particles could theoretically be encoded. In practice, this number is difficult to obtain because of spectral overlap and sample inhomogeneities. Also, despite the increased photostability of quantum dots, fluorescence quenching is still possible, casting uncertainty on using relative intensity measurements as a reliable encoding method.

Another encoding strategy has used sub-micron metallic rods. The sub-micron metallic rods are prepared by electrodeposition of metals on a porous membrane in alternating strips of controlled thickness. Different reflection characteristics of the various metals are used as a barcode for identification purposes. Reflection spectroscopy does not have the disadvantage of photobleaching inherent with fluorophores. Additionally, fluorescent analytes do not interfere with the particle signal. Deposition of rods is a relatively complex process, however, and may be difficult to apply as an encoding strategy where, for example, a large number of codes is desirable because each rod must be brought into focus in an optical reader (such as a microscope) in order to read out the codes. There remains a need for encoding strategies at the microscale.

DISCLOSURE OF THE INVENTION

The invention concerns a particle having a grey scale code embedded in its physical structure by refractive index changes between different regions of the particle.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of a multi-layer encoded particle of the invention; and

FIG. 2 illustrates a preferred embodiment method of fabricating
5 encoded particles.

BEST MODE OF CARRYING OUT THE INVENTION

The invention concerns a particle having a grey scale code embedded in its physical structure by refractive index changes between different regions of the particle. A change in the refractive index is preferably
10 obtained by varying porosity formed in the particle. Reflections taken from the particles produce an optical signature, in the visible and/or non-visible wavelengths. In preferred embodiments, the number of peaks, their locations, and intensities can be used to produce a high number of unique optical signatures exhibiting grey scale codes. In preferred embodiment formation
15 methods, a porous encoded structure is produced by an etching process during which the etching conditions are varied during pore formation according to a computer generated waveform designed to produce a grey scale coding. A dicing may be conducted to form individual encoded particles having a range of small sizes, e.g., from hundreds of nanometers to hundreds of microns.

20 Methods and particles of the invention are applicable to a variety of industries, including but not limited to drug discovery, biological screening, chemical screening, biological labeling, chemical labeling, *in vivo* labeling, security identification and product marking. Various attributes of the particles and methods of the invention enable a wide range of applications in various
25 industries. The small size of the particles facilitates ready incorporation into various hosts, e.g., products, test kits, assays, powders (such as explosives for identification), pastes, liquids, glass, paper, and any other host or system that can accept small particles. *In vivo* detection is enabled by biocompatible particles of the invention, which may then be queried, for example, through
30 tissues using near infrared and infrared wavelengths that penetrate tissues.

In accordance with the aforementioned exemplary aspects and applications of the inventions, preferred embodiment particles are identified by the grey scale code inherent to the reflectivity spectrum of their varying porous structure. In another aspect of the invention, matter, e.g., biological or chemical matter, is hosted by the porous structure and the particle becomes a tag identifying the matter hosted by the pores. In another aspect of the invention, a variance in the reflectivity spectrum of an encoded particle can indicate the presence, absence or quantity of matter within the particle's pores.

Referring to FIG. 1, a preferred embodiment encoded particle 10 is shown in cross-section. The encoded particle 10 includes a porous thin film 12. The porous thin film 12 having varying porosity is shown in FIG. 1 as being formed on a substrate 14. However, embodiments of the invention include particle structures released from a substrate upon or from which they were initially formed. The thin film 12 is encoded to produce an interference pattern in the reflectivity spectrum that forms an optical signature including a grey scale code. Particles 10 of the invention may be specifically encoded by controlling etching conditions according to a computer generated waveform during formation of the particle 10.

The porous thin film 12 may be formed of any porous semiconductor or insulator. In preferred embodiment particles of the invention, porous silicon is used to form the thin film 12. Controlled anodic etching of crystal silicon in hydrofluoric acid solution permits control of both the porosity and thickness of porous thin film 12. The time of etching controls the thickness of a porous layer, while the etching current density controls the porosity. The thicknesses and porosities of thin films 12 are controlled in accordance with a computer generated waveform.

Porous silicon is a preferred material for the thin film 12. Porous silicon has a number of demonstrated advantages. For example, porous silicon has been demonstrated to be biocompatible. In addition, the surface chemistry of oxidized porous silicon is effectively that of silica. Accordingly, the surface

chemistry is well understood for biochemical derivatization and ligand immobilization.

In preferred embodiments, the thin film 12 is formed to include a receptor material within the porous structure. The purpose of the receptor is to bind a particular analyte of interest. Exemplary receptors (also referred to as binders) are disclosed, for example, in U.S. Patent No. 6,248,539 entitled "Porous Semiconductor Based Optical Interferometric Sensor". Receptor molecules may be adsorbed or otherwise associated with the porous silicon thin film 12 by any approach that leads to the tethering of the receptor molecules to the porous thin film 12. This includes, without limitation, covalently bonding the receptor molecules to the semiconductor, ionically associating the receptor molecules to the layers, adsorbing the receptor molecules onto the surface of the layers, or other similar techniques. Association can also include covalently attaching the receptor molecules to another moiety, which is in turn covalently bonded to the porous thin film 12, or binding the target molecule via hybridization or another biological association mechanism to another moiety which is coupled to the porous thin film 12. Specific additional examples include receptor ligands that have been attached to porous silicon layers to produce biosensors. An analyte bound to a particle 10 of the invention becomes identifiable and traceable by the encoding provided by the particle 10.

We have demonstrated reproducibility in the spectral position and grey level (spectral height) by using waveform and spectra design in accordance with equations 1-4:

$$A_n = (A_{n\max} - A_{n\min})/2 \quad (1)$$

$$k_n = \text{frequency} = 1/\text{period} \quad (2)$$

$$y_n = A_n [\sin(k_n t - \Phi) + 1] + A_{n\min} \quad (3)$$

$$y_{\text{comp}} = [y_1 + \dots + y_n]/n \quad (4)$$

Equation (1) defines the amplitude of sine component n, which results in the spectral peak height, or grey scale of a bit. Equation (2) defines the frequency of the each sine component, which results in the spectral position of a peak, or identification of a bit (1st bit, 2nd bit, etc....). Equation (3) defines sine

component n. Equation (4) defines the composite waveform used to drive the electrochemical etch. The spectral peak position is a function of the frequency, k, of the sine component $y(t)$ of the time domain. Spectral peak position and position in k-space are synomous and related by

5 $c = \text{wavelength} * k(\text{frequency})$. Grey levels in the heights of the spectral lines can be determined based on each sine components' amplitude. Fourier analysis may be used as a modeling tool to approximate the spectra of the resulting photonic crystal in advance of the etching conducted to create the porosity pattern. The formation of a composite waveform may be achieved by the

10 addition of two separate sine components in accordance with equation (4). In a porous silicon photonic crystal, the average amplitude of a composite waveform must stay the same if the spectral line group is to maintain the same absolute spectral position after a change in one or more of the sine components' amplitude. Consider, for example, two waveforms, wf_1 and

15 wf_2, correspond to two codes of the form: Acomp (bit 1) = $(A_1 + \dots + A_n)/n$; Acomp (bits 2 . . . n) = $\{[A_1 - (x/(n-1))] + \dots + [A_n + x]\}/n$. If the second code has amount x added to the amplitude of its sine component, then the following condition must be met: $A_{\text{comp}}(\text{wf_1}) = A_{\text{comp}}(\text{wf_2})$, where Acomp is the amplitude of the composite waveform formed from the addition of wf_1 and

20 wf_2. Resultant k-space spectra will reveal that a constant position is maintained while amplitudes of sine components are changed with the above equations. When incident white light strikes the encoded film, only light containing frequencies that match the spatial frequencies of varying porosity present in the film are reflected back. This is a natural optical transform which

25 is much like a Fourier transform.

Experiments were conducted to demonstrate the invention. Grey scale samples were prepared by anodically etching p++ type, B-dope, (100) oriented silicon with <1mOhm-cm resistivity in a solution of 3:1 HF (48%, aq)/ethanol by volume. Computer generated anodic current waveforms

30 consistent with the above explanations for grey scale coding were applied and a

platinum mesh electrode was used as the counter electrode. Results were consistent with expectations.

The intensity of peaks in the reflectance spectrum is controlled by the refractive index at interfaces between thin film 12, determined by a change 5 in porosity between adjacent layers. Such change may be gradual or sharp. The position of peaks is controlled by adjusting layer thicknesses. Additional encoding is possible by variation of the relative intensities of each reflectivity peak, which can be engineered into particles 10 of the invention by adjustment of the electro chemical etch parameters to control porosity of the thin film 12. 10 A particle 10 having of the invention encodes L^N codes, where N is the number of spectral lines and L is the number of grey levels possible in each spectral line.

Referring now to FIG. 2, a preferred method for forming an encoded porous particle 10 is shown. A suitable semiconductor or insulator, 15 e.g., a silicon wafer, is selected for processing (step 14). For example, silicon wafers may be cut to size and be masked to have portions exposed for etching. An exemplary suitable silicon material is a single crystalline silicon wafer. Spatial encoding is then defined (step 16). The spatial encoding defines a range of codes over the material to be etched. Conducting a spatially resolved 20 etch allows codes to be programmed in particle-sized sections of the wafer. An exemplary spatially resolved etch is disclosed in U.S. Patent No. 5,318,676, entitled "Photolithographic fabrication of luminescent images on porous silicon structures", published June 7, 1994. In an alternative process, the step of spatial defining (step 16) is omitted. For example, a single wafer or an area of 25 wafer could be etched to include particles having a single code. In that case, other wafers could be etched to have particles having a different code. Anodic etching is then commenced, for example, in an aqueous solution of hydrofluoric acid and ethanol (step 18). Etching is then conducted with etching conditions varying according to the defined encoding strategy (step 20). A 30 grey scale code or codes of the invention are etched into the wafer. The traverse (vertical direction in FIG. 1) encoded but still connected particles may

be lifted off from the silicon wafer (step 22), for example by a high level of electropolishing current. Areas between spatially defined etch sections may be cut to separate differently encoded wafer sections. Individual particles are then separated (step 24) in a dicing that may be conducted, for example, by 5 mechanical agitation or ultrasonic fracturing. The particle separation (step 24) preferably produces micron-sized particles, e.g., particles in a range from a few hundred nanometers to a few hundred micrometers. A step of particle designation (step 26) may be conducted after the particle separation (step 24) or subsequent to step 20 or step 22. Particle designation may comprise, for 10 example, chemical modification of the porous multi-layer structure 12_I-12_N for specific biological, biomedical, electronic, or environmental applications. As an example, the particles can be modified with a receptor for a desired analyte or with a targeting moiety (such as a sugar or a polypeptide). Additionally, binding can be signaled, for example, by fluorescence labeling of analytes or 15 analyte autofluorescence. In use of particle 10, the particle can be identified by its optical signature upon binding of the designated targeted analyte. This step of designation may also be omitted in embodiments of the invention.

In other embodiments of the invention, encoded particles can be placed into a suitable hosts, namely any liquid, powder, dust, or other material 20 that will hold encoded micron sized particles of the invention. Particles placed in hosts, for example, could be used to identify the source of a manufactured powder such as an explosive. Another potential host is an animal. Particles of the invention being biocompatible may be implanted *in vivo* into an animal host. The reflectivity spectrum of preferred embodiment porous silicon 25 particles 10 of the invention, for example, encompasses the visible, near infrared, and infrared spectra. This presents the opportunity to sense the grey scale code of a particle of the invention through barriers such as living tissue.

A first example embodiment is stand-off detection. This is a chemical detection technique to identify an analyte from a distance. A particle 30 10 of the invention includes a receptor to sense a particular analyte. Both the grey scale code of the particle and an indication of binding of the analyte can

be detected in the reflectivity spectrum, for example, with use of a low power laser. The receptor, for example, can be specific to sense biomolecules or to attach the encoded particle to a cell, spore, or pollen particle.

Another preferred exemplary application of the invention is for
5 biomolecular screening via the encoded particle 10 of the invention. Millions of grey scale codes are possible with a small number of layers. A simple antibody-based bioassay using fluorescently tagged proteins has been tested. Periodic Rugate style encoding was used as described above with respect to the exemplary chemical sensing embodiments. By masking the wafer before
10 etching, well-defined slabs of particles may be generated.

The layered grey scale porous-silicon encoded structures offer several advantages over existing encoding methodologies. Porous-silicon encoded structures can be constructed that display features spanning the visible, near-infrared and infrared regions of the spectrum. Unlike encoding
15 schemes based on stratified metallic nanorods, fluorescence or vibrational signatures, encoded particles of the invention can be probed using light diffraction techniques; thus it is not necessary to use imaging optics in order to read the codes. Encoded particles may be assayed using a conventional fluorescence tagging technique, and sensitive chemical and biochemical
20 detection can also be built into the optical structure of the encoded particles, eliminating the need for fluorescent probes and focusing optics. In addition, because preferred embodiment oxidized porous-silicon encoded particles present a silica-like surface to the environment, they do not readily quench
25 luminescence from organic chromophores, and they can be handled and modified using the chemistries developed for glass bead bioassays. Silicon-based encoded particles may be readily integrated with existing chip technologies.

The use of encoded silicon particles of the invention in medical diagnostic applications has advantages over organic dyes or quantum dots. *In*
30 *vivo* studies have shown the biocompatibility of porous silicon, as well as the long-term stability of reflectance data from multilayer structures. Additionally,

the possibility of optically addressing particles at near-infrared, tissue-penetrating wavelengths without the losses associated with low fluorescence quantum yields makes these materials amenable to *in vivo* diagnostics. Finally, because the porous codes are an integral and orderly part of the porous structure, it is not possible for part of the code to be lost, scrambled or photobleached, as can occur with quantum dots or fluorescent molecules.

While specific embodiments of the present invention have been shown and described, it should be understood that other modifications, substitutions and alternatives are apparent to one of ordinary skill in the art. Such modifications, substitutions and alternatives can be made without departing from the spirit and scope of the invention, which should be determined from the appended claims.

Various features of the invention are set forth in the appended claims.